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Evaluation of Commercial-off-the-Shelf Lithium Batteries for Use in Ballistic Telemetry Systems

by Edward F. Bukowski

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14. ABSTRACT As technological advances continue to be made in the commercial sectors of portable and wireless communication products, additional advancements in battery technology have also been made. These advancements have allowed for the rapid growth of a large variety of commercially available batteries which have the capability to meet or even exceed the current power and size requirements for numerous ballistic telemetry systems. The replacement of a custom built battery with a commercial-off-the-shelf (COTS) battery would provide immediate advantages such as lower cost, shorter lead times, and higher availability. The overall objective of this report is to provide ballistic telemetry systems engineers and designers with a description of several low-cost, readily available COTS alternatives to traditional custom-made power sources.						
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1. Introduction

In an effort to minimize the cost and lead times associated with developing custom batteries for use in ballistic telemetry systems, several commercial-off-the-shelf (COTS) batteries were evaluated to see if they could be a suitable alternative. In the past, specialized batteries were needed because commercially available batteries could not meet the size, power, and/or environmental requirements of a ballistic telemetry system (*1*). These specialized batteries could sometimes cost hundreds of dollars a piece and take several months to be designed, fabricated and tested. The use of a COTS battery would greatly improve all of these factors. Several different battery types, such as Alkaline, Nickel Metal Hydride, Nickel Cadmium, Lithium Manganese Dioxide and Lithium Ion were taken into consideration. This report will present the results obtained from tests performed on Lithium Manganese Dioxide cylindrical cells.

After reviewing the characteristics of several different cylindrical cells, the 123 and CR2 models were chosen for testing (figure 1). They can typically be found in most retail stores which sell portable electronic devices and their high capacities, small size, long shelf life and high availability make them ideal candidates. In an effort to limit the possible design differences between manufacturers, samples were taken from the Duracell* and Energizer† brands for these tests. Manufacturer specifications are shown in table 1.

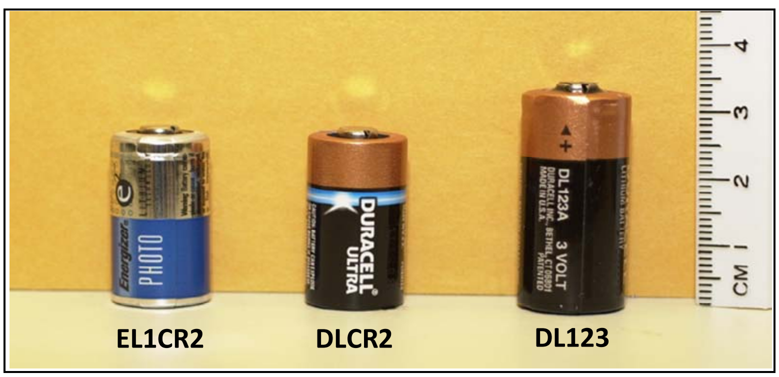

Figure 1. COTS CR2 and 123 lithium manganese dioxide cylindrical cells.

*Duracell is a registered trademark of Gillette Company, Boston, MA.
†Energizer is a registered trademark of Eveready Battery Company, Inc., St. Louis, MO.

Table 1. Manufacturer specifications for CR2 and 123 model cells.

Model Cells	Nominal Voltage (V)	Rated Capacity (mAh)	Max Discharge	Dimensions	Weight (g)
			Continuous/Pulse (mA)	Diameter/Height (mm)	
EL1CR2	3.0	800	1000/2500	15.6/27.0	11
DLCR2	3.0	800	1000/2500	15.6/27.0	11
DL123A	3.0	1500	1500/5000	—	11

2. Electrical Discharge Measurements

Individual cells were discharged at ambient temperature to determine a typical runtime at various levels of current draw. The CR2 cells were only discharged up to 1 amp since that was their maximum recommended level of discharge. Results from these tests produced runtimes from 25 min up to 2 hr. Since many of the projectile telemetry systems being developed by the Advanced Munitions Concepts Branch (AMCB) of the U.S. Army Research Laboratory (ARL) typically have a required runtime of 30 min and draw anywhere from 200 to 600 mA (*2–4*), results from these discharge measurements (table 2) show that both the CR2 and 123 cells are more than adequate to power these systems.

Table 2. Room temperature (≈20 °C) discharge results for individual CR2 and 123 cells.

Current Draw (mA)	Typical Runtime to 2.0 V Cutoff (min)		
	EL1CR2	DLCR2	DL123A
500	85.07	92.07	140.75
725	48.45	56.42	95.10
1000	25.73	28.87	60.43
1200	NA	NA	46.42

Note: NA = not applicable.

Since the cells performed very well at ambient temperature, additional discharges were conducted to determine performance at lower temperatures. The results from these discharges, shown in table 3, indicated a significant drop in runtime as compared to the runtimes at ambient temperature. As an example, at –20 °C and 500 mA, the DLCR2 had an 82% decrease in runtime and the EL1CR2 had a 74% decrease in runtime. At –40 °C and 500 mA, both cells lasted less than a minute and had a 99% decrease in runtime from ambient. Even though the cells performed poorly under the higher discharge rates, they still performed reasonably well under lower discharge rates. Therefore it is recommended that applications requiring

Table 3. Low-temperature discharge results for CR2 cells.

Temperature (°C)	Discharge Current (mA)	Runtime to 2.0 V Cutoff (min)	
		EL1CR2	DLCR2
–20	350	35.30	55.42
	500	16.55	21.87
–40	200	15.23	11.00
	250	6.10	6.48
	350	1.27	2.35
	500	28 s	53 s

low-temperature performance only use these cells if the required current draw is limited to 250–350 mA. It may be possible to increase performance by decreasing the cutoff voltage to 1.5 V per cell or by using identical cells in parallel. However, these techniques would be application specific and further discharges would be necessary before implementation.

3. High-G Shock Testing

One of the most important questions when designing for a ballistic telemetry system is whether or not the selected components will survive the harsh environmental conditions. Gun fired munitions often obtain acceleration levels anywhere from 10,000 to over 100,000 G's (*2–4*). All components used in an electronic system for these projectiles must be qualified to survive those types of accelerations. Components such as batteries are often susceptible to high shock levels based on cell construction, orientation and support. In an effort to increase the probability of success, each cell was encapsulated before testing. Encapsulation of components is a common practice in ballistic telemetry systems and is a widely accepted technique for promoting component survivability (*5–7*). In this case, the encapsulant should give extra vertical support and improve the overall integrity of the cell.

Multiple shock tests were performed on both the 123 and CR2 cells while mounted in both vertical (figures 2 and 3), and horizontal (figures 4 and 5) orientations. The cell voltage was monitored for each test and different loads were applied to simulate an active electronic system. Ideally, the cell potential should not change throughout the duration of the shock pulse. Each cell was then discharged postshock and the experimental results compared to the expected results.

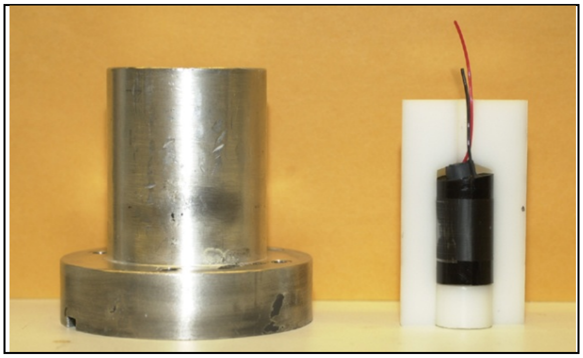

Figure 2. Shock fixture and encapsulated cell for vertical shock tests.

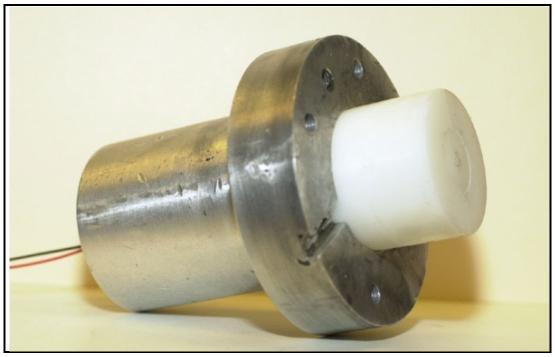

Figure 3. Vertical shock fixture and battery holding sleeve.

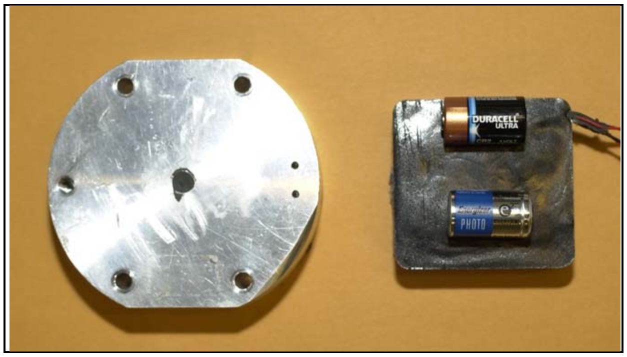

Figure 4. Shock fixture and cells for horizontal shock tests.

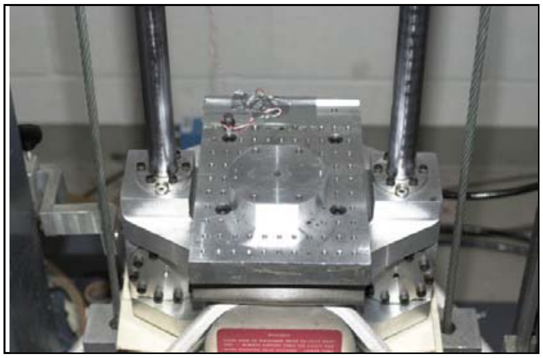

Figure 5. Horizontal shock fixture mounted to ARL impact test machine.

3.1 123 Cells in a Vertical Orientation

The first set of tests were performed on the 123 model cells in a vertical orientation. The ARL high-G impact table was used to expose the cells to acceleration levels ranging from 10 up to 35 kG's. The test set included three DL123 cells which were shocked multiple times while under a 500- or 725-mA load. Test results, some of which are shown in figures 6 and 7, indicated that all of the DL123 cells experienced major voltage dropouts during and immediately after the impact event. Measurements taken after testing indicated that two of the three cells no longer had any voltage potential. The remaining cell had a voltage measurement of about 3 V, but would immediately drop down to 0 V when a load was applied. Based on these results, it can be concluded that these cells experienced catastrophic failures due to the impact event and can not be used with any degree of confidence in a ballistic environment. No further tests were conducted with the 123 cells because of these failures.

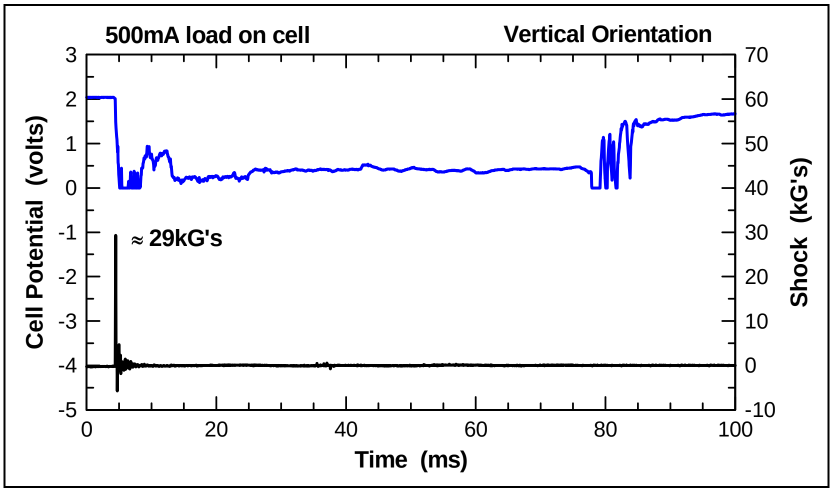

Figure 6. Test results for DL123 cell no. 2.

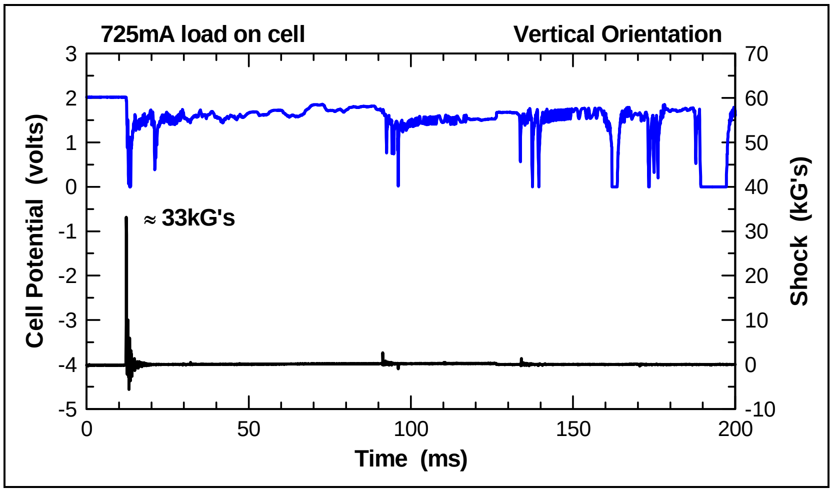

Figure 7. Test results for DL123 cell no. 3.

3.2 CR2 Cells in a Vertical Orientation

Conversely, test results for the CR2 cells were much more promising. Four DLCR2 cells and four EL1CR2 cells were shocked 2–3× each while under a 500-mA load. Test results indicated that the cell voltage remained almost constant, less than 50-mV change, throughout the impact event, as shown in figures 8 and 9. There were also no failures or significant voltage dropouts seen during any of the vertical drop tests conducted. Post-shock measurements suggested that the impact event had no lasting effect on the cells as they still held their potential and their discharges were similar to those of unshocked control cells, seen in figures 10 and 11.

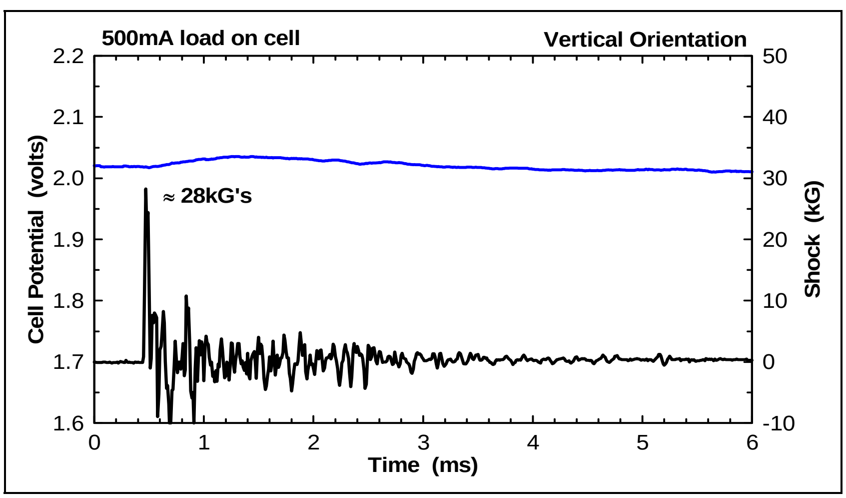

Figure 8. DLCR2 cell no. 3, shock test no. 2.

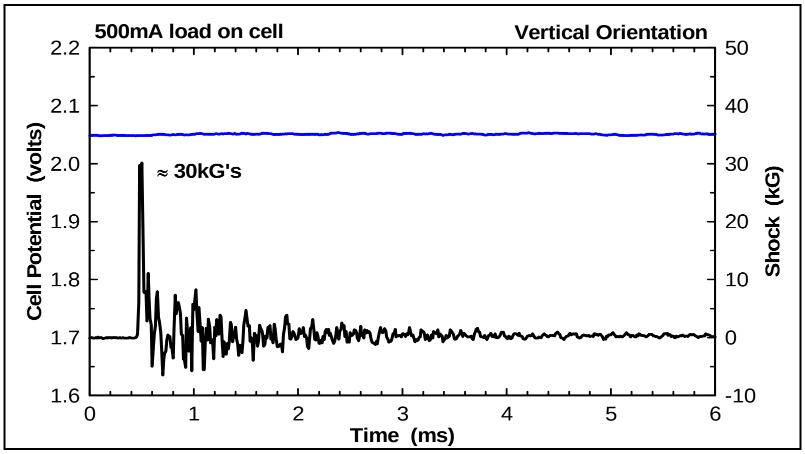

Figure 9. EL1CR2 cell no. 3, shock test no. 2.

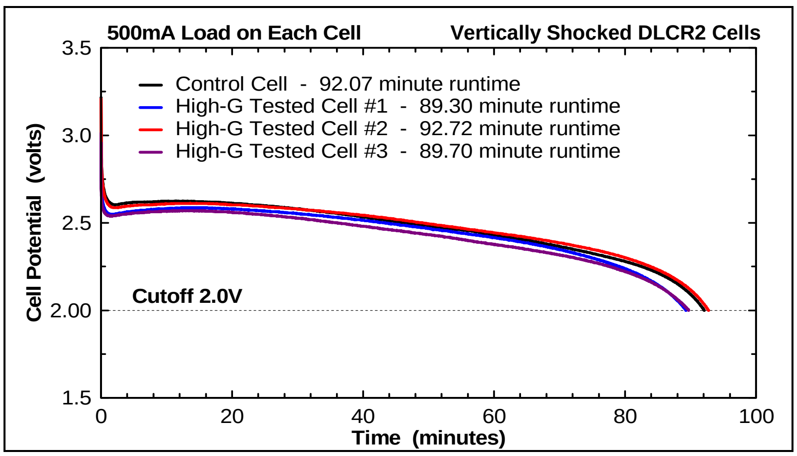

Figure 10. Comparison of discharge curves: shocked DLCR2 cells compared to unshocked control cell.

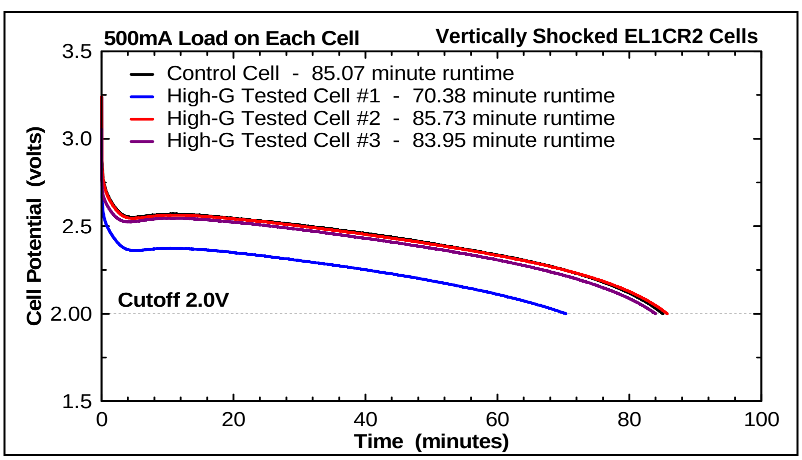

Figure 11. Comparison of discharge curves: shocked EL1CR2 cells compared to unshocked control cell.

3.3 CR2 Cells in a Horizontal Orientation

After successfully surviving high-G accelerations ranging from 10 to 35 kG's in a vertical orientation, shock testing was continued with the CR2 cells mounted in a horizontal orientation. An identical test plan was followed with the cells being tested both with and without a load applied and then electrically discharged afterward. The only other difference between the horizontal and vertical tests, aside from cell orientation, was that the cells were tested two at a time. A sample space of two DLCR2 cells and two EL1CR2 cells was used. Each cell was shocked twice and then discharged. Once again, the cells performed very well under high-G conditions as no substantial voltage dropouts were caused either during or after the impact event. Results were typical of those shown in figures 12 and 13. Postshock discharges were also completed and the resultant curves were very similar to the discharge curve of an unshocked control cell. A comparison of these discharges is shown in figures 14 and 15.

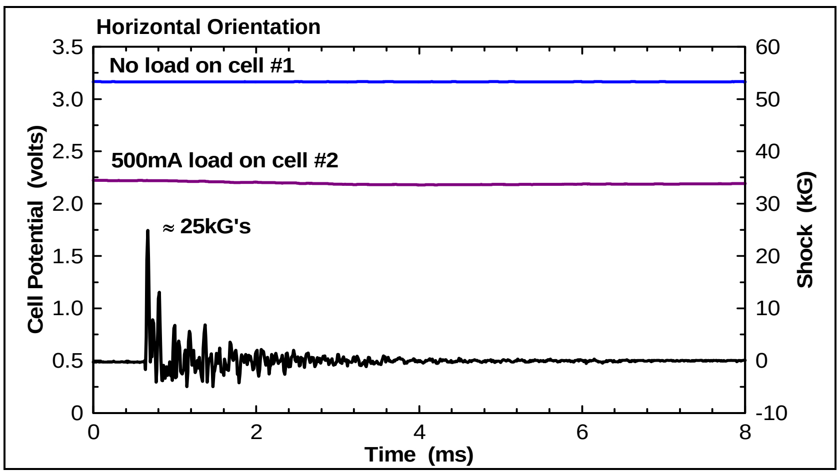

Figure 12. DLCR2 cells 1 and 2, shock test no. 1.

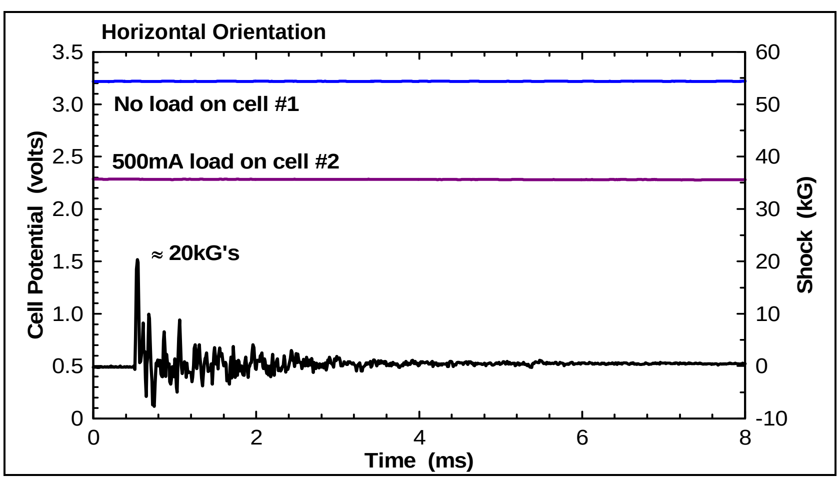

Figure 13. EL1CR2 cells 1 and 2, shock test no. 1.

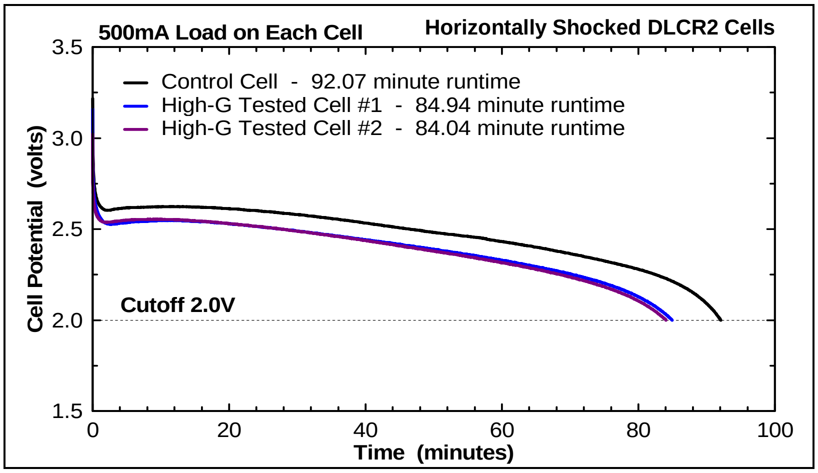

Figure 14. Comparison of discharge curves: shocked DLCR2 cells compared to unshocked control cell.

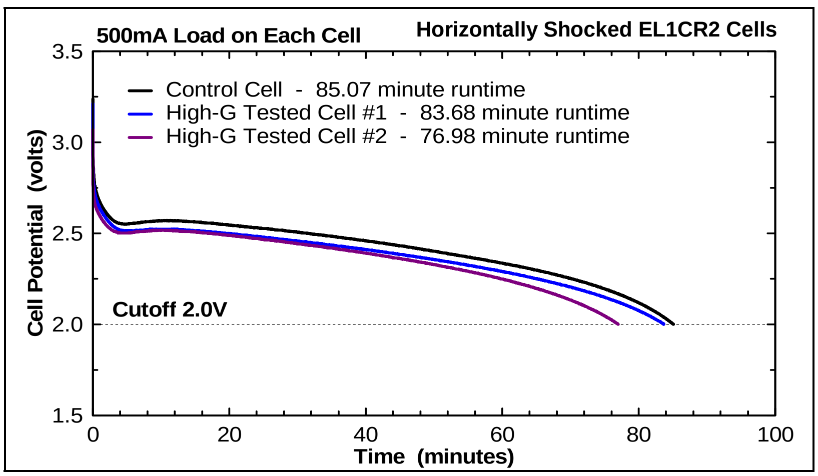

Figure 15. Comparison of discharge curves: shocked EL1CR2 cells compared to unshocked control cell.

3.4 Airgun Testing of CR2 Cells

The shock testing completed up to this point had been performed on an impact shock test machine capable of achieving accelerations up to 35 kG's. Based on the promising CR2 shock test results obtained so far, additional testing was performed at acceleration levels up to 100 kG's. Since the impact shock test machine could not reach these levels, the 4-in airgun located at the ARL Adelphi Laboratory Center (ALC) was utilized. The airgun provides acceleration pulses which are not only higher in amplitude, but also longer in duration (500–1000 μs, depending on acceleration level) than those of the impact shock test machine (typically 50–100 μs). The airgun pulses also do not have the high frequency content seen in the pulses obtained from the impact shock test machine. The only drawback to using this system was that the cells could not be monitored during the impact event. Therefore, all of the cells were shock tested without a load applied and postshock discharges were compared to those of an unshocked control cell. The airgun test carrier is shown in figure 16, and CR2 cells for airgun testing are shown in figure 17.

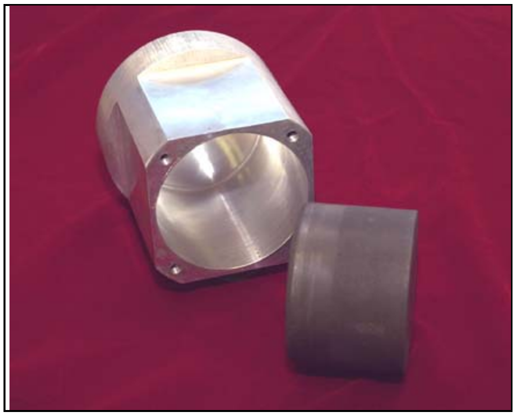

Figure 16. Airgun test carrier.

Figure 17. CR2 cells for airgun testing.

Three airgun tests were performed with desired accelerations of 60 kG's peak amplitude for the first test and 100 kG's peak amplitude for the second and third tests. Multiple CR2 cells were included in each test and the resulting measured acceleration levels are shown in figure 18. DLCR2 and EL1CR2 measurements are shown in tables 4 and 5, respectively.

Airgun test results indicated that while there were no catastrophic failures during the 60-kG test, the cells were degraded by the impact. Postshock discharges indicated that the tested cells had discharge curves both shorter in runtime and lower in amplitude than that of an unshocked control cell, as shown in figures 19 and 20. The only positive aspect of the 60-kG results is that

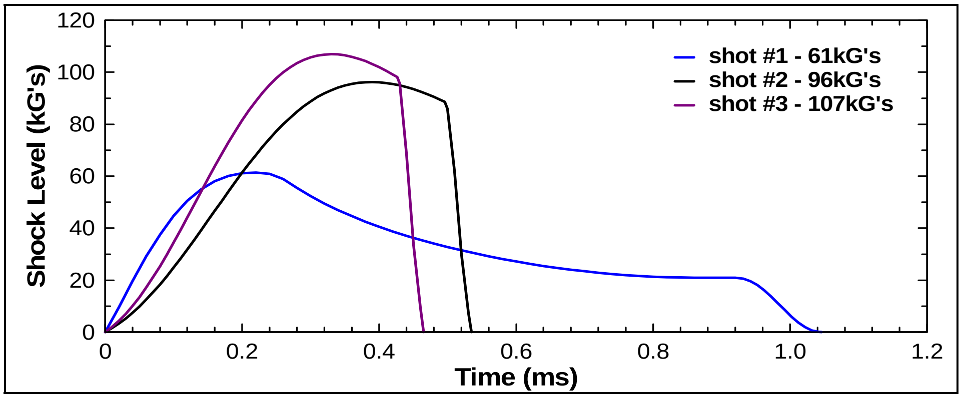

Figure 18. Airgun acceleration pulses.

Table 4. DLCR2 measurements.

	Open Circuit Voltage		Postshock Runtime (min)
Cell No.	Preshock	Postshock	500-mA Load to 2-V Cutoff
Shot no. 1 – 61 kG's			
D1	3.23	3.13	84.88
D2	3.23	3.21	82.00
Shot no. 2 – 96 kG's			
D3	3.21	3.21	84.90
D4	3.22	3.22	66.37
Shot no. 3 – 107 kG's			
D5	3.23	3.00	74.50
D6	3.22	0.54	NA

Note: NA = not available.

Table 5. EL1CR2 measurements.

	Open Circuit Voltage		Postshock Runtime (min)
Cell No.	Preshock	Postshock	500-mA Load to 2-V Cutoff
Shot no. 1 – 61 kG's			
E1	3.25	2.99	57.92
Shot no. 2 – 96 kG's			
E2	3.24	3.24	56360
E3	3.24	3.24	80.80
Shot no. 3 – 107 kG's			
E4	3.25	3.25	0.00
E5	3.27	3.32	25.30

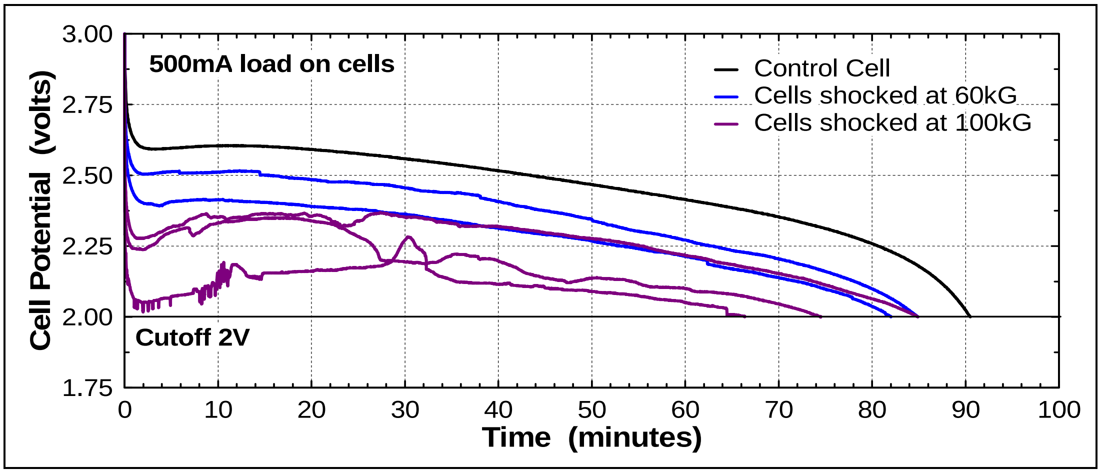

Figure 19. Discharge curves for DLCR2 cells airgun tested cells compared to unshocked control cell.

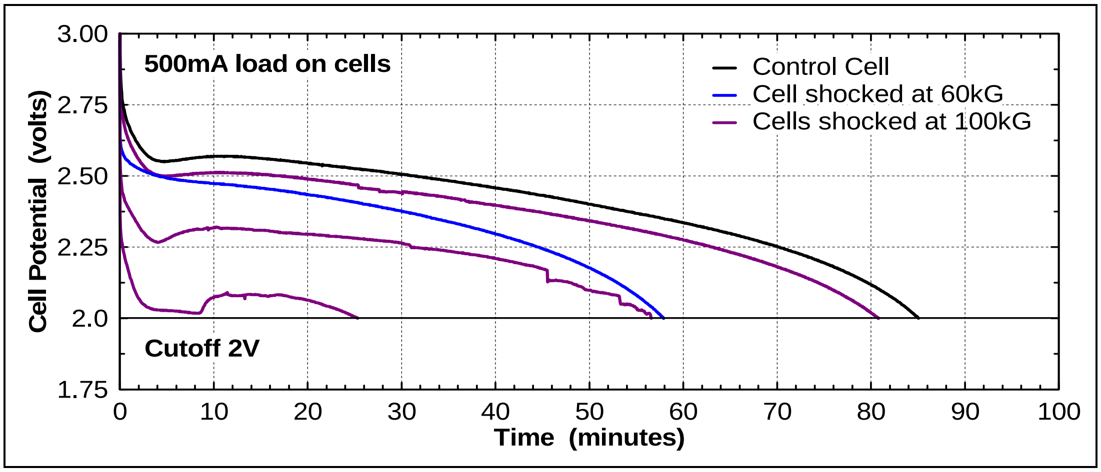

Figure 20. Discharge curves for EL1CR2 cells airgun tested cells compared to unshocked control cell.

the shapes of the discharge curves are still representative of a typical discharge and the runtimes are also still of an acceptable length. However, given that the cells were indeed degraded, it would appear that a 60-kG acceleration level would represent the limit of operation for these cells. This conclusion is further supported when looking at the results from the 100-kG tests. In these cases, the post-shock discharge curves no longer represent a typical discharge curve, which has a smooth, gradual decline. Runtimes for these cells are also greatly decreased and several cells were no longer functional postshock.

4. Spin Testing

In addition to the high levels of linear, setback acceleration present in most ballistic environments, components must also be able to function and survive under high spin conditions (*2*, *4*). Spin rates from 60 up to 300 Hz are commonplace and the CR2 cells must be able to survive if they are to be used in a ballistic telemetry system. A flight simulator, shown in figure 21, was used to test the CR2 cells at spin rates of 100, 200, and 225 revolutions per second (rps). Each spin test included two DLCR2 cells and two EL1CR2 cells, shown in figure 22. The cells were positioned in a vertical orientation and placed at distances of 0.5 and 1.25 in off center.

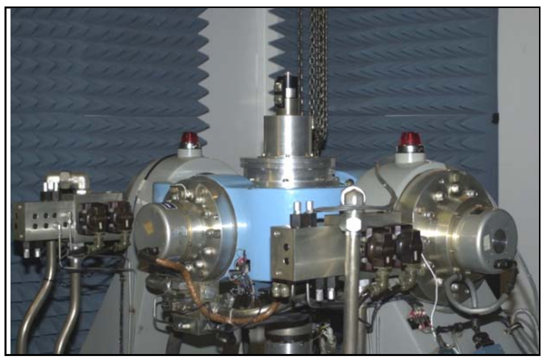

Figure 21. Flight simulator.

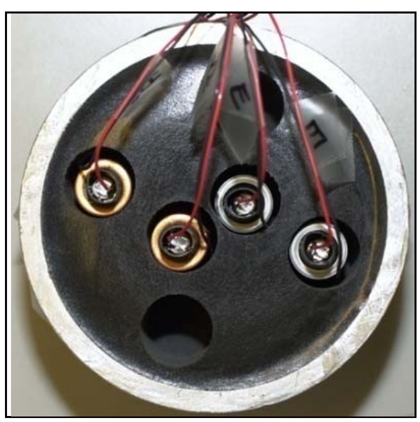

Figure 22. CR2 cells in spin fixture.

During each test, the CR2 cells had a 500-mA load applied to them and the output of each cell was recorded throughout the spin cycle. The output of a stationary control cell was also recorded. Results from these tests showed that the CR2 cells performed extremely well while under spin, as seen in figures 23 and 24. A comparison of the test cells with the control cell shows that their outputs are almost identical throughout each test. The only difference between the cells under test and the control cell noted is that the test cells have a lower measured potential, which is most likely caused by the additional loading placed on the cells due to the slip ring and cabling. When the cells were discharged post spin, they produced runtimes in the range of 80–85 min and had discharge curves similar to that of an untested cell. These results indicate that the high spin had no lasting effect on the cells and little to no effect on the overall performance of the cells either during or after the spin event.

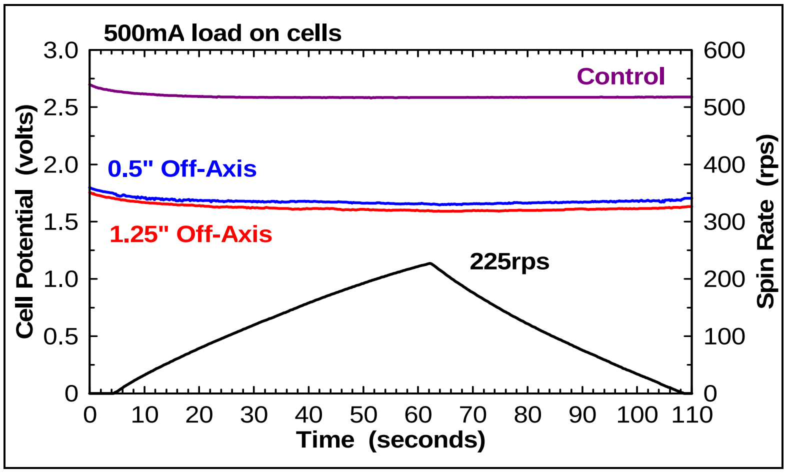

Figure 23. DLCR2 225 rps spin test results.

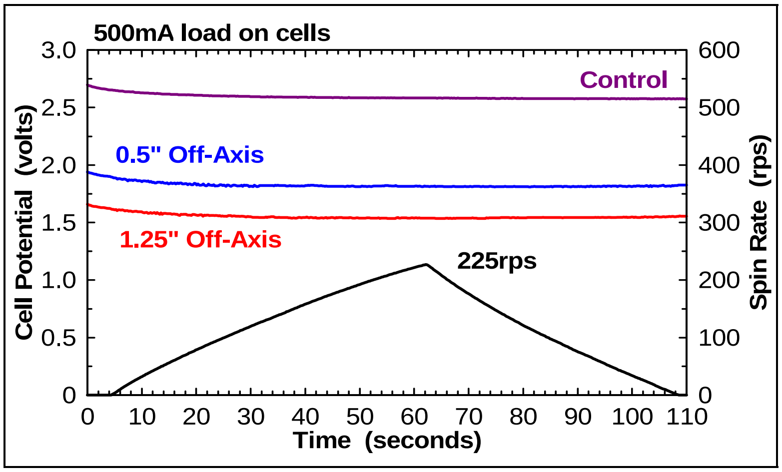

Figure 24. EL1CR2 225 rps spin test results.

5. Integration of CR2 Cells Into Ballistic Telemetry Systems

Based on the survivability and performance of the CR2 cells with respect to high levels of acceleration and spin, the CR2 cells have been integrated into several ballistic telemetry systems. One example is that of a NATO Standard Telemetry Fuze (NSTF). The NSTF is an on-board instrumentation system that replaces the standard NATO nose fuze with telemetry and sensors (*7*, *8*). This system uses multiple CR2 cells to power the on-board electronics. Preliminary qualifications of this system included flight tests in which the NSTF was attached and flown on a modified M831 projectile. Setback accelerations in the range of 20–30 kG were successfully recorded and no CR2 failures occurred.

Another system which has used the CR2 cell as a power supply is the Mortar Diagnostic Fuze (MDFuze), shown in figure 25. This system replaced the standard fuze with telemetry and sensors and was successfully flown on several 60-mm mortars (*9*). Setback accelerations around 7 kG were seen for these tests and no CR2 failures were reported.

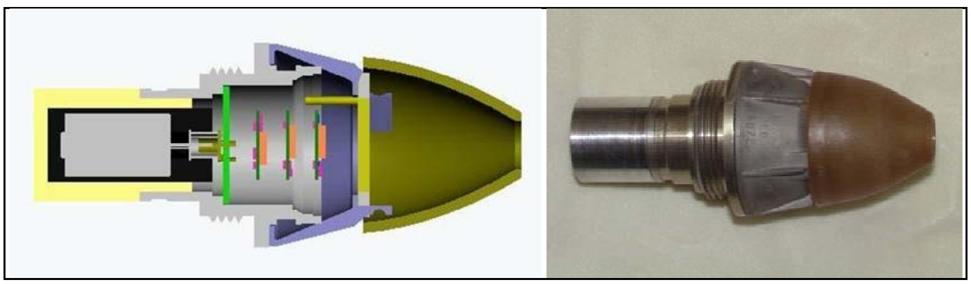

Figure 25. Mortar diagnostic fuze.

A third system which has incorporated the CR2 as a power supply is the Telemetry Data Unit (TDU), shown in figure 26. This telemetry system is a stand alone unit which has been used to provide a variety of in-bore ballistic diagnostics (*4*, *10*). This system has been used to record and transmit setback accelerations from 20 to 40 kG in the ARL airgun. The system has also been used to provide in-bore pressure and set-back acceleration data for a modified M829A2 KE round. Tests using this type projectile produced setback accelerations around 50 kG’s. Once again, the system worked successfully and no CR2 failures were reported.

The successful integration and implementation of the commercially available CR2 cells into these ballistic telemetry systems is strong evidence that these cells can indeed be used as a reliable power supply capable of withstanding very harsh ballistic environments.

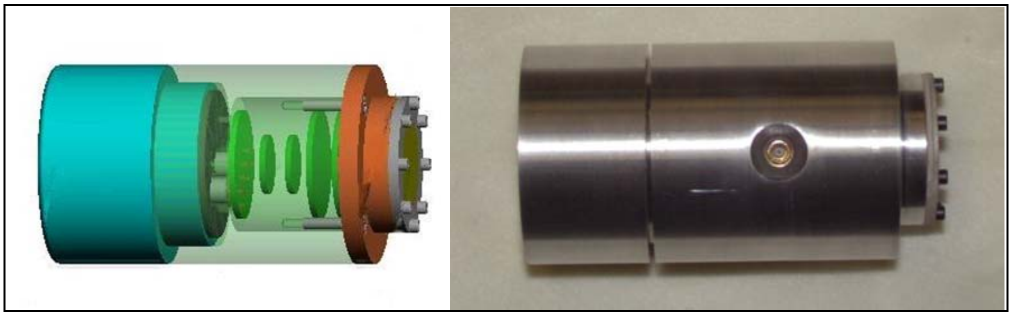

Figure 26. Telemetry data unit.

6. Conclusions

The CR2 and 123 lithium manganese dioxide batteries were initially considered for integration into ballistic telemetry systems based on their availability, shelf life and high current capacities. Before these cells could be used however, it needed to be known whether or not they could both perform and survive under harsh conditions such as high set-back acceleration and high spin. Preliminary shock testing up to 35 kG's showed that the 123 cells can not survive a ballistic environment and that the CR2 cells can not only survive, but also provide the same electrical performance as that of an unshocked cell. Additional testing in both vertical and horizontal orientations produced similar results and reinforced the notion that these cells could be used in a ballistic telemetry system. However, once airgun testing was performed, it was discovered that these cells did have a limit regarding shock tolerance. At accelerations up to 35 kG's, there were no major changes in performance. At accelerations around 60 kG's, the cells survived but their performance was decreased. And at accelerations around 100 kG's, the cells had major drops in performance and even some complete failures. These results show that use of these cells should be limited to a maximum within the 35- to 60-kG range. High spin testing at rates of 100, 200, and 225 rps showed that spin had little to no effect on the performance of the cells. The tested cells produced results almost identical to cells which had not been tested. Based on these test results, the CR2 cells have been integrated into several ballistic telemetry systems and used successfully without any failures. The culmination of all of this information gives the conclusion that the survivability and performance of the CR2 cells make them ideal for use in a variety of ballistic telemetry systems.

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